

STUDY OF ONE MAN LUNAR FLYING VEHICLE

SUMMARY REPORT

FACILITY FORM 602	N 69-39203	
	(ACCESSION NUMBER)	(THRU)
	21	1
	(PAGES)	(CODE)
	CR-101943	31
	(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

REPORT NO. 7335-950012

JULY 1969

Prepared under Contract NAS9-9044


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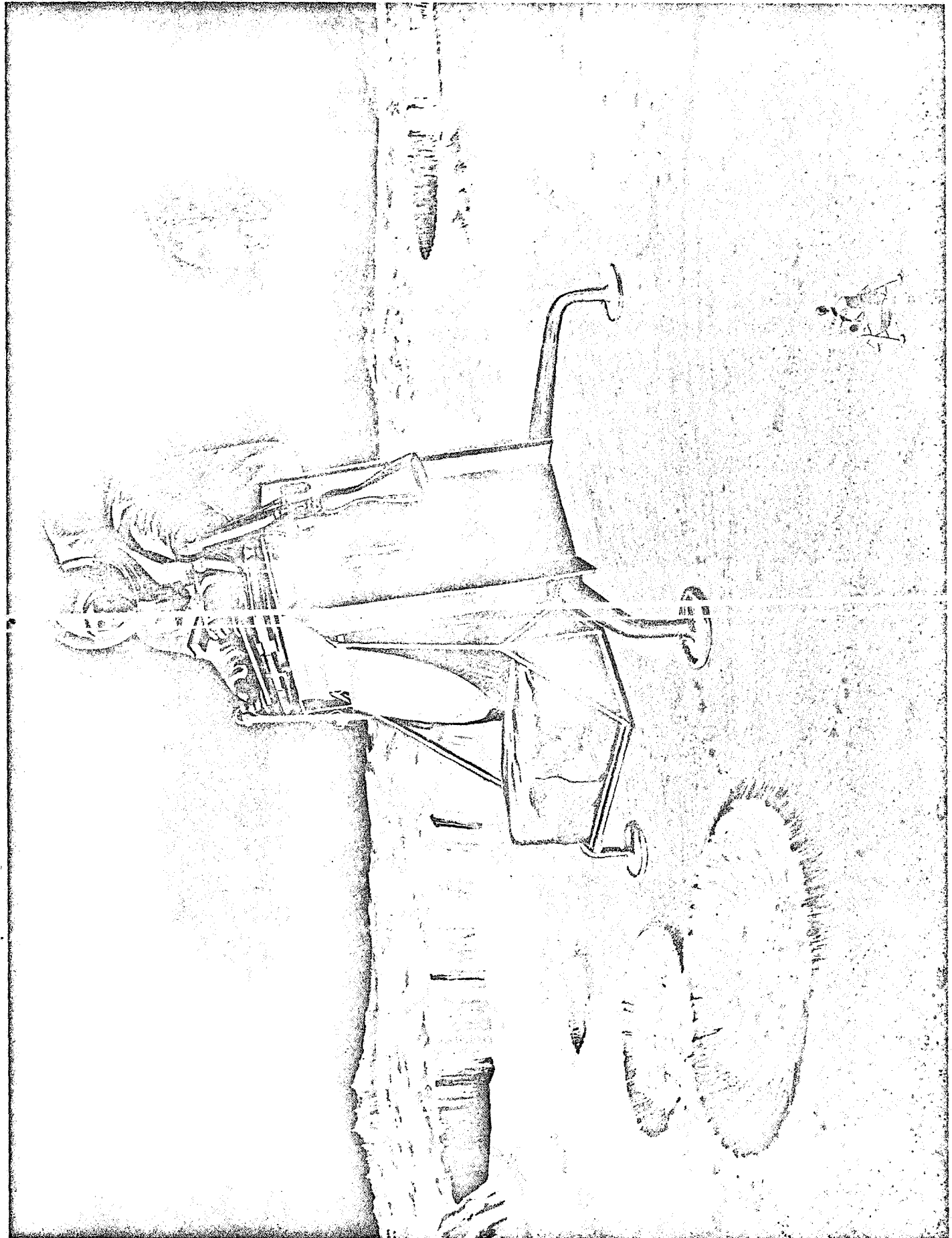
For

National Aeronautics and Space Administration
Manned Spacecraft Center

Houston, Texas



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FOREWORD

This report summarizes the results of a study of a One Man Lunar Flying Vehicle, conducted for the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, under Contract NAS 9-9044.

Detailed information can be found in Bell Aerosystems Report No. 7335-950010, Study of One Man Lunar Flying Vehicle Final Report.

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I. INTRODUCTION

Prior studies of lunar surface missions established the desirability of providing the lunar explorer with mobility aids to enhance his exploration capability and his safety. It was shown that flying mobility could increase scientific time at remote sites and permit exploration of many features of interest to scientists but inaccessible by surface travel. Scientific return can be improved by making observations and measurements from the vantage point of altitude. The use of flyers enhances overall mission safety because (1) rapid return to the LM can be accomplished in the event of developing contingencies in other systems or natural events; e.g. the suit, PLSS, LM, solar flares, etc. and (2) for a given amount of scientific time at a remote site(s), total EVA time is minimized. Furthermore, the flying vehicle is ideal as a rescue vehicle because of its speed. By addition of auxiliary propellant tanks and a simple guidance system, the exploration flyer might provide a capability for emergency ascent to lunar orbit.

The prior Lunar Flying Vehicle (LFV) and Manned Flying System (MFS) contracts, conducted for NASA by Bell Aerosystems established the feasibility of providing a small lunar flyer using present state-of-the-art technology and components from the Apollo and other space programs. The vehicle investigated in the MFS study was required to carry two astronauts to a round trip radius of 15 miles, employ dual LM type augmented controls, and meet LM landing criteria. The resulting vehicle carried the two astronauts seated side by side, and incorporated four LM RCS type rockets modified for throttling, a sophisticated electronic guidance and control system, and a modified LM type landing gear.

This vehicle weighed over 400 pounds (earth weight) empty, and carried 600 pounds of LM propellants. The

weight of the vehicle and its propellants dictated that this mobility aid could be made available only on those lunar missions which employed a dual Saturn V launch. It became apparent that a gap would exist between the initial landings on which no mobility aids would be used, and the later dual Saturn V missions. This gap could be filled only if a mobility aid could be developed whose system weight was compatible with the modified LM payload capability of approximately 1000 pounds. Mission application and vehicle design studies were therefore initiated on a smaller, shorter range, less sophisticated one man flyer. These studies showed that many of the early mission requirements could be met with a small one man, stand-up, vehicle employing a mechanical thrust vector control system, and a helicopter type landing gear.

Prototype flight tests in free earth flight, and also in gimbal and tether type simulated lunar flight, with both shirt sleeved, and Apollo pressure suited pilots, demonstrated the feasibility of the standup configuration with the simple all mechanical flight controls. Lunar vehicle design studies showed that this vehicle would weigh about 200 pounds empty, and should carry about 300 pounds of LM propellant. Furthermore, Grumman studies of LM utilization showed that between 300 and 1500 pounds of propellant would be available in the descent stage tanks after landing, and that this propellant could be withdrawn for use in the lunar flyer. Thus, only the flyer dry weight plus its support equipment would come from the LM payload allotment. In view of these developments, NASA instituted a new study of lunar flyers to optimize the design and develop system specifications for a simple lightweight one man vehicle. This report presents the results of the study conducted by Bell Aerosystems under NASA Contract NAS 9-9044.

II. STUDY OBJECTIVE

The objective of the study is to optimize the design and develop system specifications for a simple one man lunar flying vehicle. The vehicle is to include only equipment mandatory for safe flight, provide a flight range of 10 to 15 miles, and carry a payload of zero to 370 pounds.

The study is to evaluate alternative configuration concepts, and for the best concept, provide design and performance data, and total program funding, schedule, and manpower resources requirements.

III. RELATIONSHIP TO OTHER NASA EFFORTS

This vehicle is related specifically to the Apollo lunar landings starting in mid 1972. Figure 1 shows the lunar flyer schedule and a two mission per year Apollo Lunar Landing schedule. Also shown is an alternate early lunar flyer, utilizing an existing hydrogen peroxide propulsion system from the Bell Aerosystems rocket belt.

The lunar vehicle, can, of course, be used on future dual Saturn V missions, where additional propellant quantity will enhance the flyer capability. The lunar flyer can also serve, with uprating of the engines, as a Mars flyer. With the addition of a radio command and autopilot system, it can perform as a remote controlled lunar or Mars explorer.

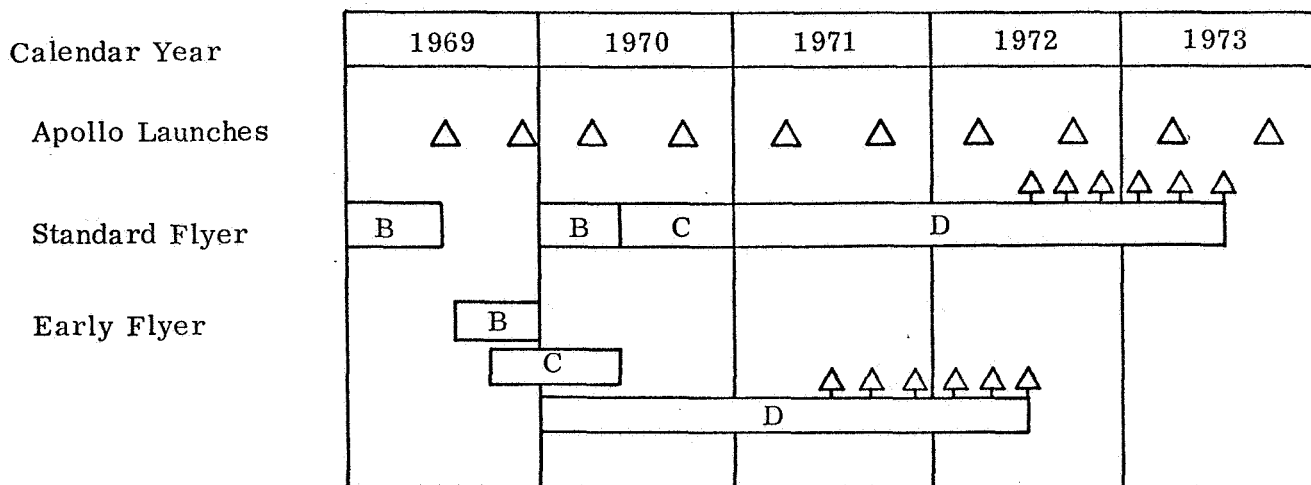


Figure 1. Lunar Exploration Schedule

IV. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

The organization and task sequence of the study is presented in Figure 2. Mission requirements for the lunar flyer are to provide for:

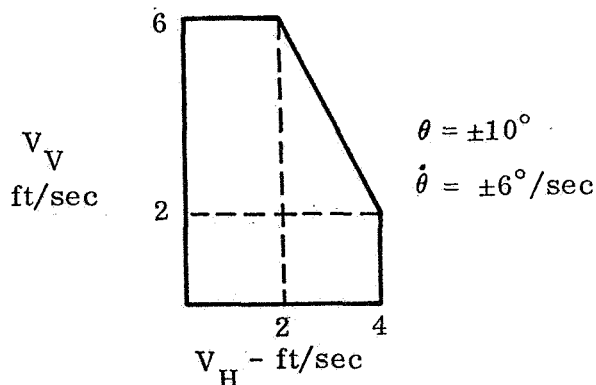
1. Horizontal and vertical mobility
2. Reconnaissance and exploration over rough terrain
3. Up to three-month lunar storage prior to use
4. Up to 30 sorties during one lunar mission
5. Total range of 10 to 15 miles
6. One man deployment
7. Flyer payloads from 0 to 370 pounds (alternate - 100 pounds maximum)
8. Rescue of disabled astronaut (requirement deleted during study)

In explanation of Item 7, it was required to determine the vehicle dry weight reduction if the maximum payload capability is reduced from 370 pounds to 100 pounds. In regard to Item 8, it was required to determine the effect of deleting the requirement to carry a disabled astronaut, while retaining a capability to carry a 370 pound payload.

System and subsystem requirements were provided in the contractual statement of work, were derived from mission requirements, and were developed during the study. These are:

1. Vehicle dry weight target - 180 pounds
2. System dry weight target - 450 pounds (2 vehicles and LSE)
3. Vehicle propellant load - 300 pounds of LM propellants
4. Minimum complexity - only mandatory flight equipment
5. Communications by PLSS radio
6. Maximum use of available components

7. Design to Saturn V/Apollo environmental requirements
8. Maintain propellants temperature within 40°F to 100°F
9. Design engine, structure, and landing gear for a future 25% vehicle weight growth.
10. Total engine thrust range - 50 to 300 pounds
11. Regulated pressure-fed propulsion
12. Two flyers stowed on LM descent stage
13. Refuelable from LM descent stage
14. Takeoff and landing within refueling distance from LM
15. Landing envelope



This study is based on current plans to use the basic LM descent stage for early lunar exploration. Two flyers and support equipment will be carried to the moon, stowed in two of the LM descent stage quadrants, and will utilize propellants remaining in the descent stage tanks after landing. Furthermore, the vehicle is designed for compatibility with the present Apollo soft pressure suit and PLSS, or any future suit and PLSS of equal or improved mobility and weight.

V. DATA AND RESULTS

A. VEHICLE DESCRIPTION

The vehicle recommended to meet the flyer requirements, shown in Figure 3 and in the frontispiece, evolved through a systematic analysis and comparison of crew positions, engine number and location, flight control concepts, tankage arrangements, and landing gear types. In each case, selection was made on the basis of optimizing safety and reliability, followed by consideration of weight, performance, cost, development risk, LM stowage volume, and convenience of handling and service operations. Reliability was maximized by simplicity of design and operation, and by use of conservative design margins.

The vehicle is supported and controlled by two engines designed for throttling from 150 to 25 pounds thrust each, and for operation at a low temperature to provide high reliability. Engines are pivoted in pitch and mechanically linked to handlebar type controllers. Yaw control is by differential pitch motion. Roll control is by differential throttling. Throttle and on-off valves are mechanically linked to the astronaut operated controls. Propellant is contained in two tanks similar to the LM RCS tanks but without bladders. The engines are mounted high enough on the vehicle to minimize the effect of the rocket exhaust plume on the lunar surface and permit safe takeoff and landing close to LM. The vehicle and astronaut are protected from the rocket and plume heat by a multi-layer thermal shield. Thermal control is attained by passive means, employing thermal coatings and multi-layer insulation techniques similar to those used on the LM.

The landing gear consists of four cantilevered legs and pads. The legs fold for stowage on LM, but once unfolded, no moving or sliding joints are required.

Payloads, up to and including a second astronaut, are carried on a specific mission designed pallet attached to the front of the vehicle. An astronaut restraint system is provided to restrain lateral motion but to permit knee flexing to reduce vertical loads on the upper torso and PLSS. The display panel mounted on the left hand controller provides propellant system status monitoring information. The principal structural element is a four inch deep honeycomb platform upon which is mounted a box beam surrounding the propellant tanks. Structure and landing gear is primarily titanium.

The vehicle dry weight is 235 pounds, however, engine thrust and the vehicle structure and landing gear have been designed for a future dry weight growth of 25%

to 294 pounds. An analysis of the effect of reducing the payload capability from 370 pounds to 100 pounds, shows that vehicle present dry weight could be reduced by 9.7 pounds.

B. CONTROL SYSTEM

The control system study established control sensitivity and maximum power requirements, investigated methods of generating control moments, compared handlebar type and Apollo side arm hand controllers, evaluated pressure suit effects on vehicle control, and evaluated the benefits of control or stability augmentation. Parametric shirt sleeve and space suit multi-axis control sensitivity studies established the preferred control sensitivities. It was found that the entire range of control sensitivities, resulting from changes in payload and propellant load were acceptable. However, a pre-takeoff pitch trim adjustment is required, as a function of payload, to keep control motion within acceptable limits.

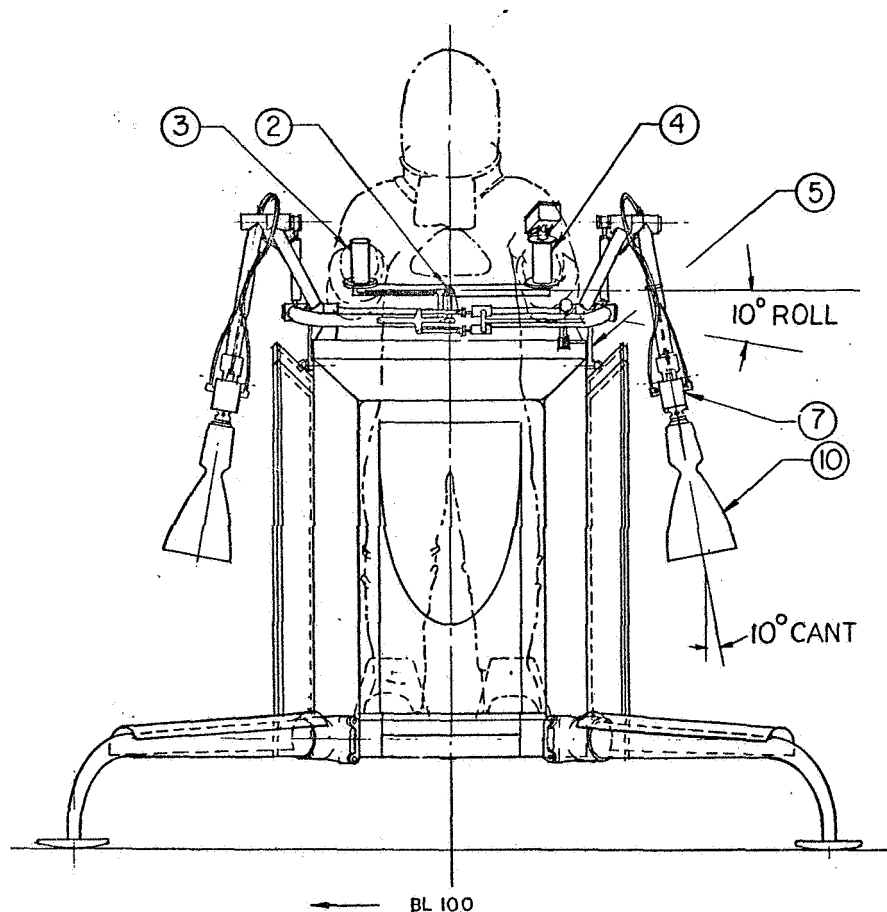
Control moment methods investigated included kinesthetic or body motion, gimbaled lift engines with pivots above and below the vehicle c.g., sliding engine, and differential throttling of multiple engines. It was determined that the kinesthetic configurations had marginally low control power which resulted in poor handling qualities. Because of these inferior handling qualities and difficulties in earth simulation and training for kinesthetic control, this method of control was dropped from further consideration. A pivot location below the c.g., in pitch resulted in poor pilot ratings and a noticeable deterioration in hover performance at low sensitivities. Pivots high, translating thruster and differential throttling configurations showed acceptable handling qualities at all sensitivities above 1 deg/sec²/deg.

The handling qualities for the high pivot, manually controlled, unaugmented vehicle were found to be acceptable. The Pilot Cooper ratings by four operators ranged from 2½ to 4½ for the complete range payload, propellant load, and flight conditions anticipated in lunar use. Workload measurements indicated that 20% to 50% of the pilot's attention is required.

Direct comparison tests demonstrated the following benefits of augmentation, using handlebar and Apollo hand controllers as measured by the Cooper ratings: Hand Controller Unaugmented 5.0-6.0; Handlebar Controller, Unaugmented 3.0-3.5; Handlebar Controller Augmented 1.0-2.0; Hand Controller, Augmented 1.0-1.5. Workload measurements corroborated this trend. ΔV usage proved

LEGEND

- 1 PITCH CONTROLLER PIVOT AXIS
- 2 ROLL CONTROLLER PIVOT AXIS
- 3 THRUST CONTROLLER
- 4 YAW CONTROLLER
- 5 THRUST POSITIONER ASSY
- 6 PROPELLANT ISOLATION VALVES (2)
- 7 PROPELLANT SHUTOFF VALVE (2)
- 8 PROPELLANT SHUTOFF VALVES CONTROLLER
- 9 PROPELLANT THROTTLE VALVE
- 10 THRUST CHAMBER (2) 150Lb MAX. THRUST, THROTTLEABLE
- 11 INSTRUMENT PANEL
- 12 MULTI-LAYER HIGH TEMPERATURE INSULATION
- 13 LANDING GEAR PLUME SHIELD
- 14 LANDING GEAR FOLDING HINGE
- 15 ASTRONAUT RESTRAINT HARNESS (2)
- 16 PAYLOAD PALLET
- 17 LM/OMLFV INTERFACE FITTINGS (3)



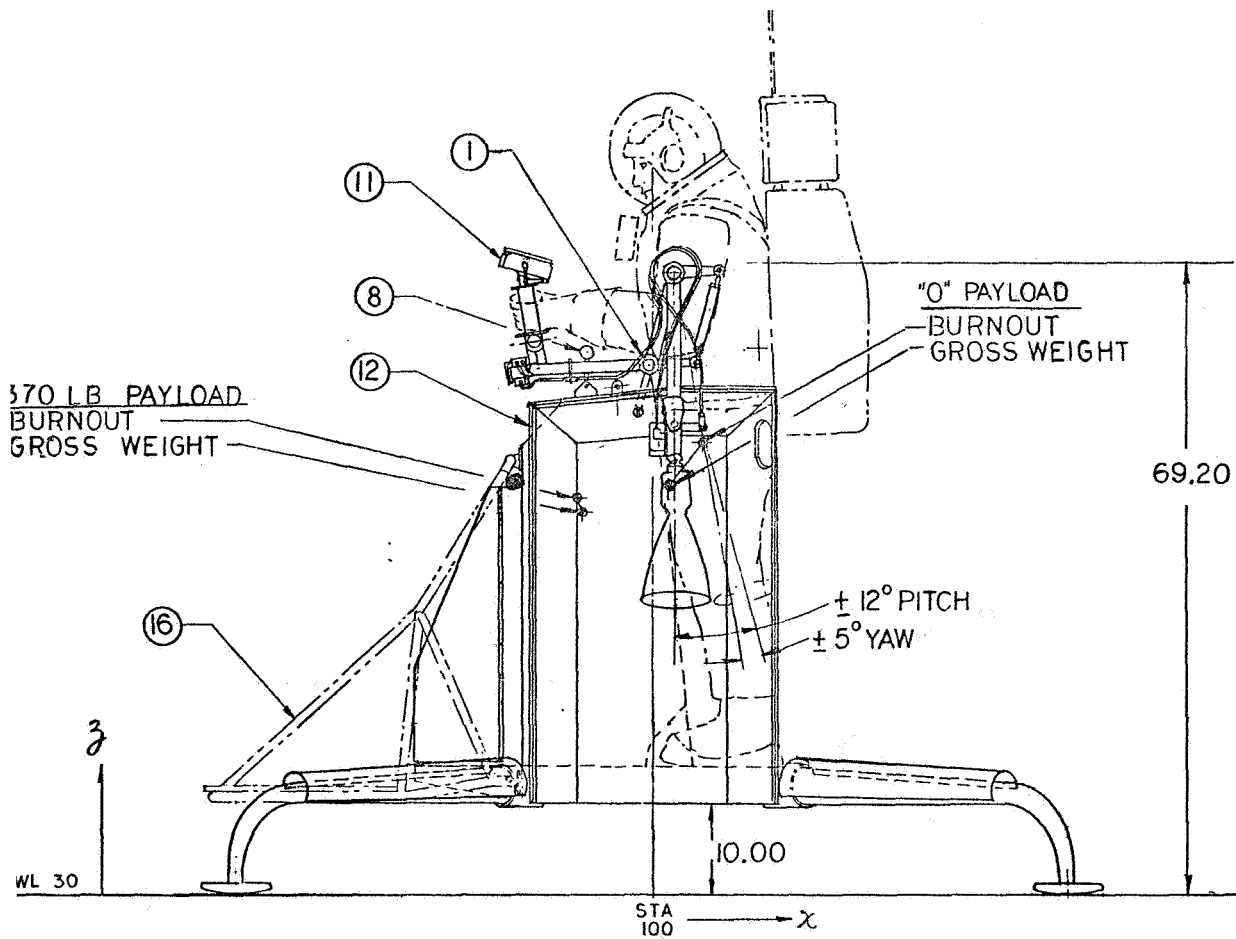
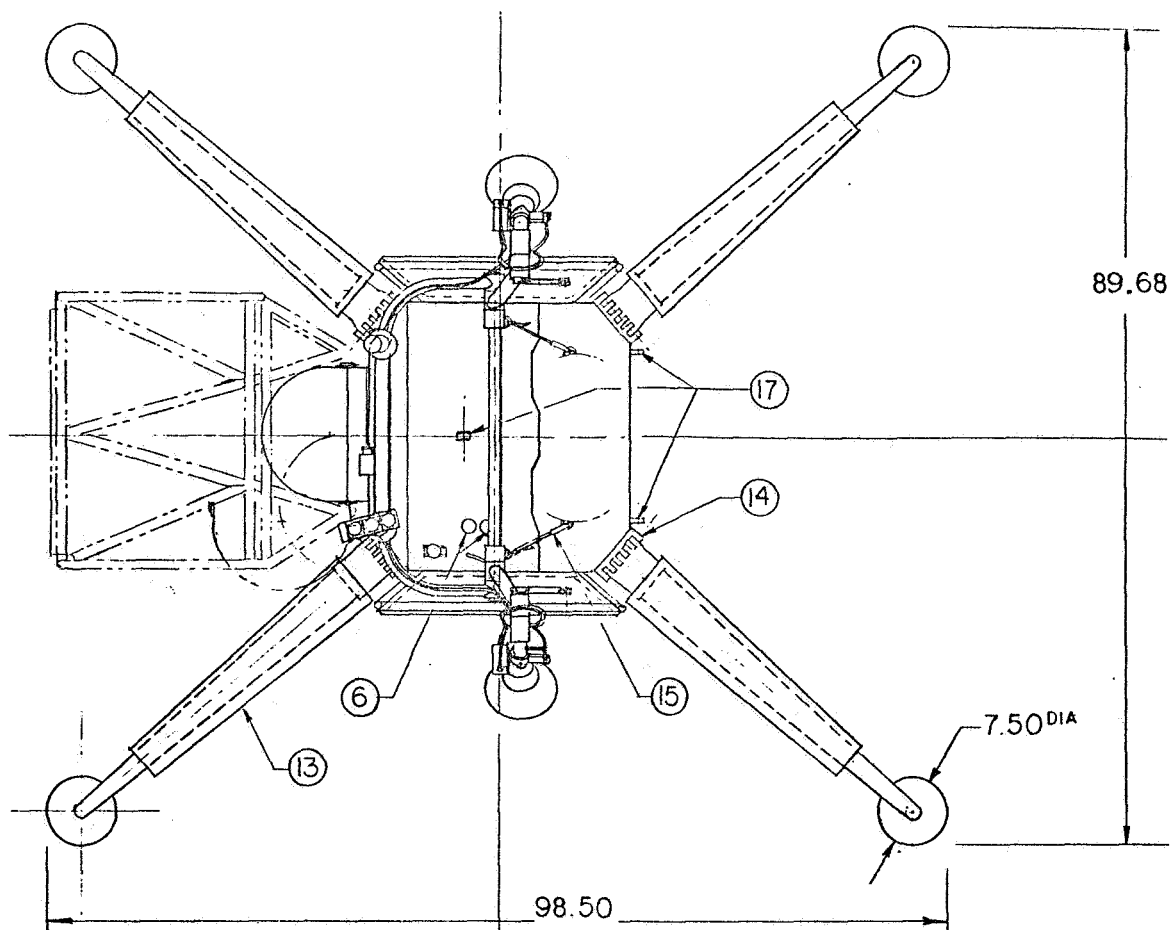


Figure 3. General Arrangement

insensitive to control system and controller alternatives. Incorporation of a three-axes, gyro type stability augmentation system (SAS) would impose a weight penalty of about 30 lb. The increased complexities of SAS with its resulting reliability, operational, cost, and training penalties were felt to outweigh the non-essential improvement in handling qualities, so SAS is not recommended.

An all mechanical spring damper control augmentation system is attractive as a means of obtaining most of the benefits of SAS with but a small fraction of its penalties. More development is recommended to establish design requirements for control and for trim. At present, the un-augmented, handlebar controller system is recommended.

C. LANDING GEAR

The criteria established for the OMLFV landing gear is shown in Figure 4. The velocity envelope is based upon data gathered from LLRV, LM-LLRF, and Bell Aero-systems' small tethered 1/6 g vehicle experience. The values for attitude, attitude rate, and ground slope are considered to be conservative for this vehicle since the pilot/control capability is sufficient to keep all these parameters close to zero in the hovering mode.

A review was made of the data from all Surveyor landings which indicated that each Surveyor behaved in a similar fashion with regard to soil/foot pad interaction.

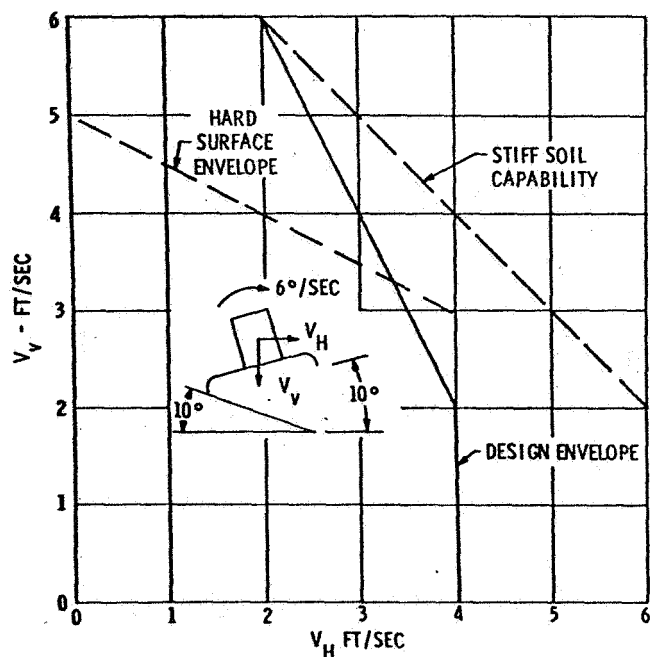


Figure 4. Final Design Gear Stability

Since the Surveyors landed in a variety of locations with similar results, the lunar surface/footpad interaction can be used as a predictable shock absorbing medium for a piloted landing vehicle.

A landing dynamic analysis digital computer program used in the landing gear study was verified by comparing the results with a similar program developed by Bendix for LM analysis which was in turn checked with model drop tests.

Landing gear concepts studied during the program included the four-legged strut/pad type gear, three-legged systems, and inverted tripod legs with energy absorption. The strut pad gear was selected because it can meet the landing criteria, employs no moving parts, and has a smaller stowed volume than a three-legged system. It provides good landing capability, minimum weight, and is easy to deploy. Each leg is a tapered curved titanium tube with a diameter of 4 inches at the root, $1\frac{1}{2}$ inches at tip, and 0.060 inch wall thickness. Footpad diameter was optimized at $7\frac{1}{2}$ inches. The stability capability of this gear on stiff lunar soil is shown in Figure 4. Also shown is the capability for landing on a hard unyielding surface.

D. PROPULSION SYSTEM

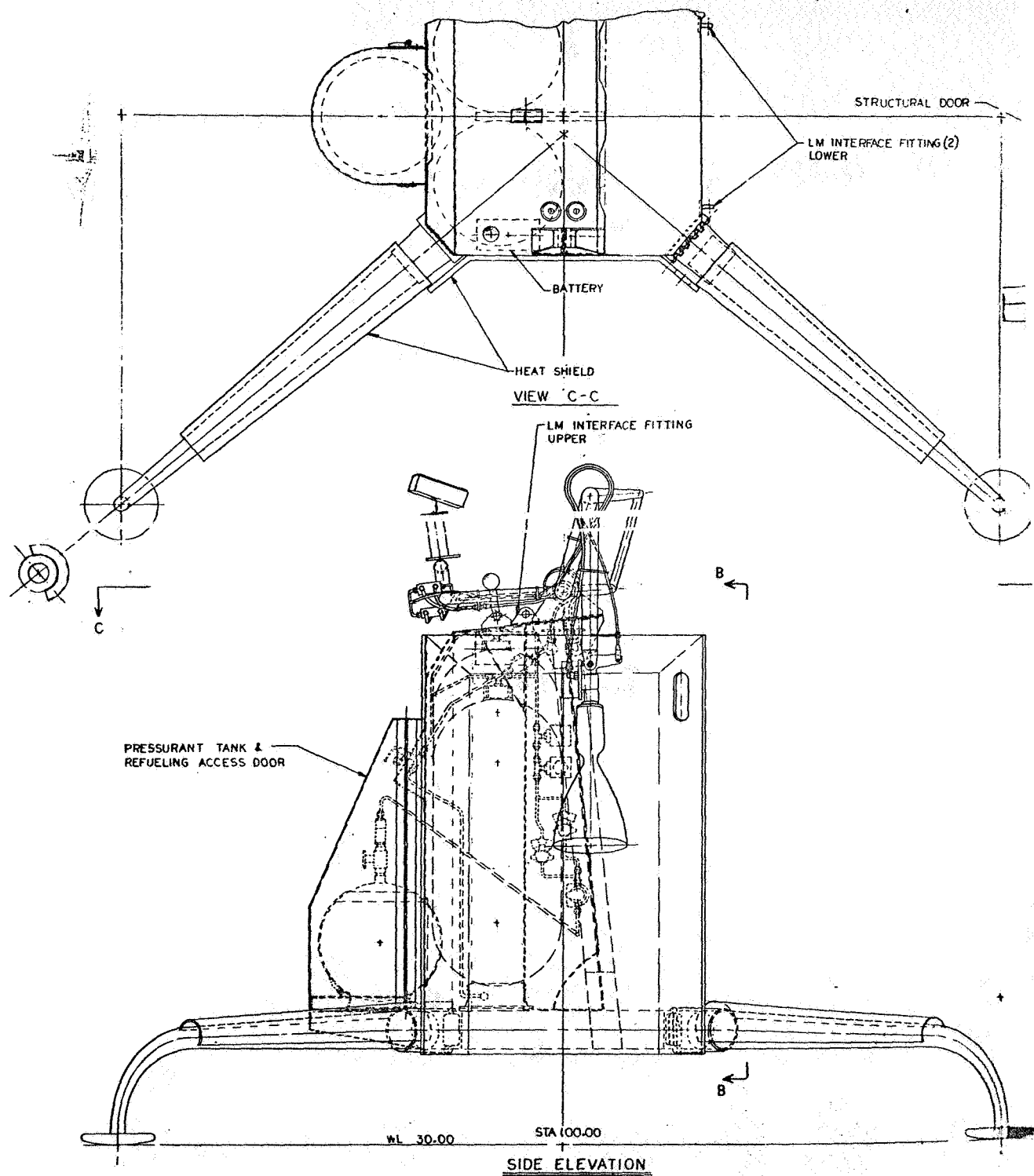
A parametric study was conducted to establish the optimum thrust range, feed pressure, chamber pressure, and area ratio for one engine, two engine, and four engine, pressure fed propulsion systems. This optimization study, along with a vehicle configuration study, led to the design of the propulsion system shown in Figure 5.

A preliminary selection of typical components was made using space qualified hardware with a minimum modification wherever possible. Only the propellant tanks and engines must be designed and optimized for the OMLFV application; all other components require only minor modifications to available qualified hardware. Four engine manufacturers have provided data which demonstrates the capability to meet the OMLFV requirements with existing design technology.

High reliability and safety is provided by minimizing the number of components that must operate successfully, and by providing large operating margins on the design capability of these components. The flight safety and reliability of the radiation cooled thrust chamber is dependent upon temperature margin. An operating temperature of 2200°F was selected to provide a 900° margin on the 3100°F capability of the silicide coatings.

The cavitating venturi throttle valves, engine shutoff valves, and tank isolation valves are all mechanically

CONTROL SYSTEM
SUPPORT FITTING



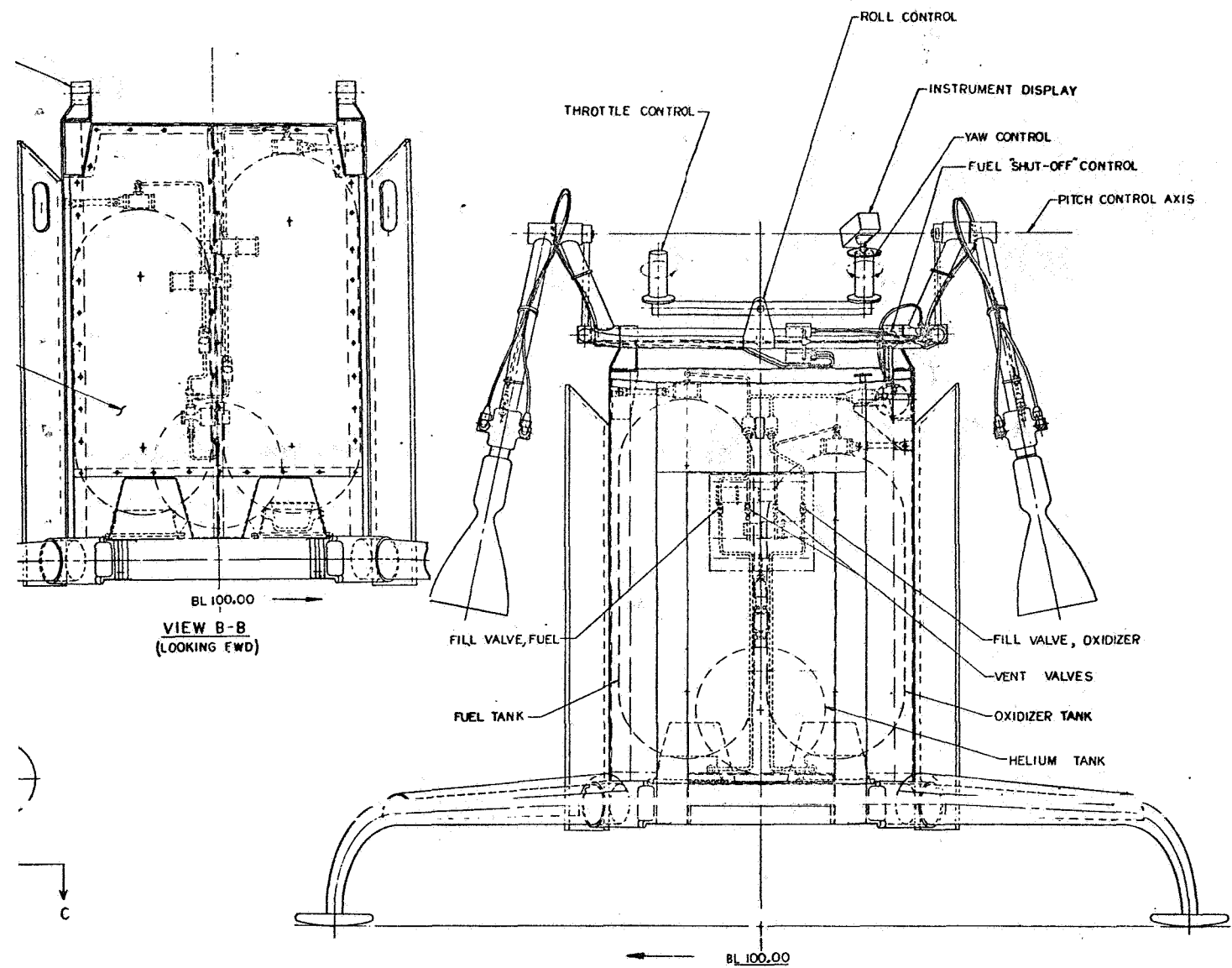


Figure 5. OMLFV Inboard Profile

actuated by the pilot, to eliminate the complexity of electrical, pneumatic, or hydraulic actuation systems.

The engine throttle valve and actuation system can be exercised under operating pressures in preflight checks, to insure smooth operation prior to takeoff. Any contamination which might be present is cleared by wide open throttle operation during the ascent and acceleration phase of the flight.

The engine shutdown valve can be made fail-safe for all operating conditions including startup, shutdown, and in-flight actuation failures. The only other moving parts in the propulsion system are the check valves (made quad redundant) and the regulator. The regulator is backed up by the relief valve and tank ullage volume which permits blow down operation for a safe landing.

E. THERMAL

An analysis was conducted to establish insulation and coating requirements to maintain the vehicle and propellants within acceptable temperature limits during storage and operation, and to protect the vehicle and astronaut from engine and exhaust plume heat.

Thermal design of the lunar flying vehicle is completely passive. A plume/radiation shield is provided at the sides of the vehicle to preclude excessive heating of the structure due to direct engine radiation and plume heating. This shield employs LM type coatings and multilayer insulation. The outer layer is of thin Inconel 600 sheet backed by 20 layers of Polyimide 0.5 mils thick and aluminized on both surfaces. The inside of the shell which encloses the tanks is also insulated with the same material. A curved shield is attached to the top of each landing gear strut to protect it from exhaust plume heating. Tank isolation is employed to minimize heat transfer from the warm structure to the tanks. The overall thermal design is adequate for maintaining the propellant well within its 70 ± 30 degrees temperature limits. A 3 degree propellant temperature rise will be experienced during a typical three-day mission.

F. PERFORMANCE

The vehicle performance, expressed as range versus payload, is shown in Figure 6 for several sortie types and two different flight profiles. The dashed line indicates the performance which is obtainable when flying a "Nap-of-the-Moon" type flight profile where the velocity has been limited to 100 ft/sec. This surface contouring type of flight has been demonstrated on earth with small rocket powered vehicles and helicopters. The solid line indicates the performance obtainable when flying a conventional type flight

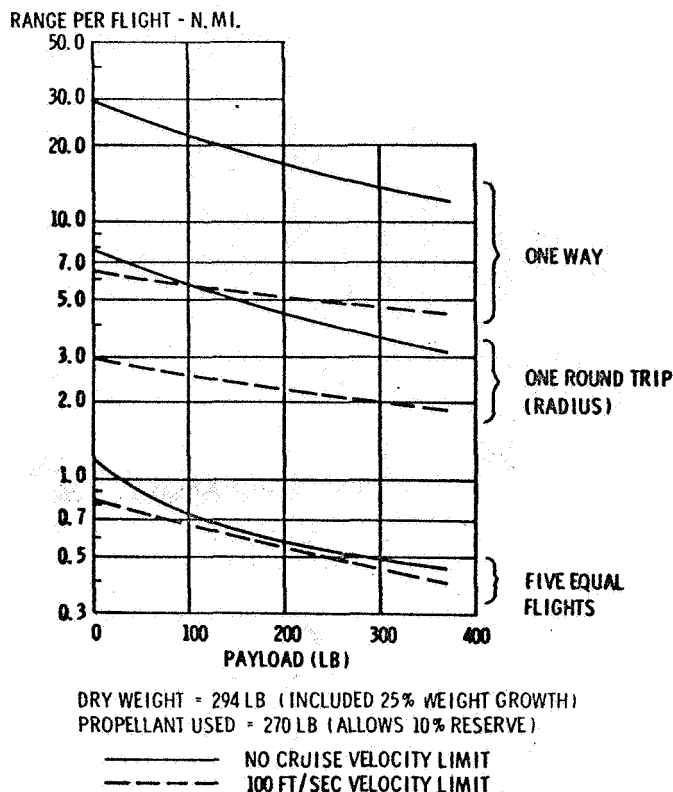


Figure 6. Vehicle Performance

profile where more nearly optimum altitudes and velocities are attained. This flight profile makes allowances for pilot errors in the early portions of flight to preclude overshooting of the destination. Navigation and flight path control can be achieved through the use of a timer and recognized landmarks. This type of performance will be attainable on later missions after more earth and lunar experience is gained in flying this type of flight profile.

G. OPERATIONS

The operations study effort identified the flyer related activities at KSC and the lunar surface operations. At KSC the activity takes place at three locations; the operations and checkout building, the static test complex, and the weight and balance building. The arrival of the flyers is scheduled to permit checkout, test, and mating in parallel with lunar module checkout activities. The associated ground services equipment required for KSC checkout/test of the One Man Lunar Flying Vehicle is identified.

Lunar surface activity is divided into two broad categories; (a) that involved in initial deployment, fueling, and checking of the flyers (called the activation phase) and (b) that involved with its flight use (called the exploration phase). Detail time-line analyses were conducted to establish these times. The time required to activate two flyers is 83 minutes. The time associated with flyer use during a normal exploration EVA cycle is 30 minutes.

H. LM INTEGRATION STUDIES

Two flyers can be installed in two quadrants of the LM descent stage. This requires only folding of the flyer legs. The effect of the flyer and its attachments and thermal protection on LM center of gravity, structural hard points, and RCS exhaust plume is acceptable.

Drawings were prepared to show the installation of the flying vehicles and associated support equipment on the lunar module, and the equipment and procedure for deployment of the flyer to the lunar surface. Unloading equipment is similar to that used for ALSEP and can be used at LM tilt angles up to $\pm 15^\circ$.

Grumman studies of LM utilization indicate that 300 to 1500 pounds of propellants will be remaining in the descent stage tanks after landing, and these propellants can be extracted for fueling the flyer. This requires the addition of taps into existing LM lines, and the use of 20 foot flexible lines from LM quadrant I to the flyer.

I. FLIGHT SUIT TESTS

The flight suit/mockup tests were conducted to; (1) develop vehicle design data to insure operational compati-

bility between the suited astronaut and the vehicle (2) provide information to assist in concept selection, and (3) provide a basis for task/time-line data. A summary of the design recommendations made as a result of these suit/mockup tests is presented in Table 1.

In addition to these detailed quantitative design recommendations, a realistic definition of other design aspects, including deployment and servicing operations and equipment was obtained.

J. TRAINING

Astronauts will be thoroughly trained for conservative flyer operation in the early lunar operation phase, using procedures based on current earth flight experience. Concurrently a flight research program will be conducted to extend the operational envelope.

A 21- week flight training program has been defined. The astronaut time required is, on the average, 1 to 1-1/2 hours per day during that period. The training equipment consists of a fixed base simulator (visual), a one g free flight jet vehicle, a one g free flight rocket vehicle, and a one sixth g tethered jet vehicle. This equipment is a modification to existing equipment.

TABLE 1
SUIT/MOCKUP TESTS

AREA INVESTIGATED	DESIGN RECOMMENDATIONS
INGRESS/EGRESS	ENTRY FROM THE REAR PREFERRED
FRONT	• MINIMUM PLATFORM SIZE (38 IN. x 9.5 IN.)
SIDE	• EASE OF INGRESS/EGRESS
REAR	HAND HOLDS ESSENTIAL
CONTROLLERS	FOR TWIN HANDLE CONTROLLERS:
TWIN HANDLED	• HEIGHT 39 TO 45 IN. FROM PLATFORM
3-AXIS (APOLLO TYPE)	• 19 TO 21 IN. BETWEEN CONTROLLERS
JOY STICK	FOR 3-AXIS CONTROLLER AND THROTTLE:
SIDE BARS	• 14 TO 17 IN. FROM SUIT FACE
THROTTLE TYPES AND LOCATIONS	• 9 TO 14 IN. OFF SUIT CENTERLINE
	• GRIP FROM TOP
REACH ENVELOPES	6 IN. TO 8 IN. INCURSION INTO A 62 IN. HIGH OPENING
	21 IN. TO 24 IN. LIMIT FOR LOWERING EQUIPMENT TO THE PAYLOAD PALLET
VISIBILITY	62° TO 68° DOWNWARD VISIBILITY OVER RCU - DISPLAY PANEL TO BE LOCATED ACCORDINGLY

K. ESCAPE TO ORBIT

This study investigated modifications to the exploration flyer to give it capability for emergency return to lunar orbit.

Three flying vehicle concepts were found to be capable of accomplishment of this ascent to orbit mission. These were: (a) two, one-man vehicles, (b) one, two-man vehicle, and (c) a dual purpose vehicle capable of providing surface rescue as well as two-man ascent to orbit capability. Concepts for all three of these vehicles were developed utilizing modifications to the exploration vehicle or exploration vehicle equipment.

The one-man exploration vehicle requires the addition of a propulsion module which contains approximately 500 lb of propellant and two additional 150 lb thrust engines to carry one man to orbit.

Two exploration vehicles can be attached to a propulsion module which contains 900 lb of propellant and four additional 150 lb thrust engines to carry two men to orbit.

The dual purpose vehicle is retained at LM with sufficient propellant for a surface rescue mission. If escape to orbit is required, the tanks are filled from the LM ascent stage propellants.

For escape to orbit guidance, a four-phase flight technique was developed to achieve a 60 nautical mile orbit with continuous engine operation (T_{max} and T_{min}). The range angle selected for ascent to orbit was 20 degrees based upon a compromise between higher ΔV requirements at smaller range angles and less accurate injection into orbit at larger range angles. The equipment required to accomplish the ascent to orbit is a sight to provide attitude information and an accelerometer to provide phase termination information. After termination of the ascent, the ascent vehicle waits for the CSM to complete the rendezvous/docking maneuvers. The ascent vehicle will carry a lightweight transceiver and will work in conjunction with the VHF communication link ranging system aboard the CSM to provide range and range rate data to the CSM during rendezvous and docking. The line-of-sight angle and rate information is obtained by optical devices onboard the CSM.

L. RESOURCES PLAN

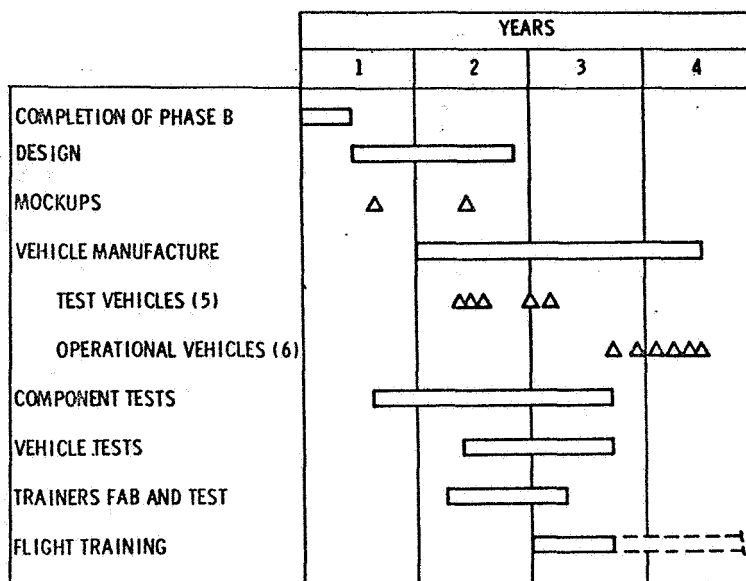
Table 2 is a summary schedule and cost for the development of the OMLFV. Delivery of the first operational vehicles occurs 33 months after go-ahead. Non-recurring costs amount to \$23.5 million and the recurring costs for vehicles and their associated lunar support equipment is approximately \$1 million per set.

TABLE 2
COST AND SCHEDULE SUMMARY

OMLFV COST SUMMARY

	MILLIONS OF DOLLARS				TOTAL
	PER YEAR				
	1	2	3	4	
NONRECURRING AND PROGRAM MANAGEMENT	4.3	12.7	6.3	0.2	23.5
RECURRING (6 VEHICLES AND LSE)	-	0.1	2.5	3.1	5.7
TOTALS	4.3	12.8	8.8	3.3	29.2

OMLFV SCHEDULE SUMMARY



VI. LIMITATIONS

There are no limitations in results of the study, in regard to the feasibility of providing flying mobility for lunar explorers. The basic methods required for all subsystems have been demonstrated, and current space hardware and present state-of-the-art technology will suffice. However, design details and performance presented in these reports must be refined by future tests. Specifically, additional suited subject/mockup tests are recommended to

establish detail design requirements for vehicle controls and for vehicle unloading and servicing equipment. Flight simulation and free flight tests are required to establish the vehicle safe flight envelope and flight instrument requirements. A more detailed definition of the mission and vehicle payload is required to complete payload pallet design and vehicle trim system requirements.

VII. IMPLICATIONS FOR RESEARCH

The study has indicated means by which lunar research can be enhanced, has provided indications of areas where additional earth research can contribute to the lunar flyer, and also has implications for a new class of simple manned earth flight vehicles.

In addition, the study has established the feasibility of providing a mobility device which will permit the lunar astronaut to explore areas inaccessible by surface travel. Because of the speed of the flyer, scientific time at remote sites will be maximized. In addition, scientific return can be enhanced by making observations and measurements from the vantage point of altitude. The flyer can contribute to astronaut safety by providing rapid emergency return to LM. With suitable modifications, the flyer can provide for emergency return to lunar orbit.

Although the feasibility of a lunar flyer has been established using present day technology, several areas of research which could contribute to lunar flight technology are discussed in Section VIII.

The results of the Lunar Flyer Study have provided data which might be applicable to a new class of manned earth vehicles. Although kinesthetic control was found to provide insufficient control power in the lunar gravity field, in earth gravity it may provide a means for great simplification of a small jet or rocket engine powered flight vehicle. In addition, the simplified all mechanical thrust vector control system also has direct application to the control of small manned earth vehicles.

VIII. SUGGESTED ADDITIONAL EFFORT

A. SAFETY, ABORT, AND HAZARD ANALYSIS

The manner in which the lunar vehicle is employed is dependent on an assessment of the risk in comparison to the scientific return. A failure and hazard analysis will be useful in exposing the higher risk hardware items, where larger safety margins or design changes should be considered, or the high risk tasks, where operational procedures should be modified to reduce the probability or consequence of human error, and will permit comparison with other vehicles, other parts of the Apollo system, or alternate versions of the vehicle.

Assessment of risk depends on an evaluation of the probability and the effect of hardware failures, and of human errors. Methods for assessing risk due to hardware failures have been widely used. A modified form of the Apollo Procedure for Failure Mode, Effects, and Criticality Analysis, Document RA-006-013-1A is proposed.

Methods of assessing risk due to human error in accomplishing complex tasks requiring judgment are possible by comparing the factors which affect the task of flying on the moon, with flying on the earth, and thus extrapolate earth experience, for which data are available, to lunar flight. It is proposed that this be accomplished by comparison of the detailed operations required, and verified by comparison of the overall flight task. In this way, a probability of safe lunar flight can be related to actual earth flight data.

B. FLIGHT RESEARCH/TRAINING PLAN AND SIMULATOR PRELIMINARY DESIGN

A high degree of confidence in the ability of astronauts to safely fly a simple one man lunar flying vehicle can be attained by conducting a coordinated flight research and training program. The OMLFV study established a preliminary flight research and training plan. It is recommended

that efforts be conducted to prepare a more detailed plan, establish simulator requirements, and prepare preliminary designs of simulation vehicles and facilities so that an early start can be made on a flight research program, and to establish training vehicle cost and schedule.

Vehicles and facilities for conducting research and training for flight in the vicinity of the moon are already in use or under development. These include Icarus, FLEEP, and the LLRF at Langley Research Center; the LLTV and 1/6 g sloping floor at Manned Spacecraft Center; the Rail/Tether Suspension System and Rocket Pogo Vehicle at Bell; and many visual simulation facilities at NASA Centers and in industry. These vehicles and facilities must be investigated to determine their applicability and modifications for one man lunar flying vehicle flight research and training.

Modified equipment includes a Pogo configuration of the Bell turbojet powered earth gravity free flight vehicle, a larger rocket powered earth gravity free flight vehicle to carry a pressure suited operator for flight duration up to one minute and a turbojet powered 1/6 g tethered vehicle, for longer duration and distance than the present Bell and LRC facilities.

A training program for both flying and servicing the LRV has been established during the current program. Improvement in this plan can be made by conferring with cognizant NASA training personnel and crews. Advantage should be taken of the unique experience being gained by those who have already been trained and worked in the lunar environment. Additionally, the training program as currently defined assumes continuity of training. However, this must be integrated with other training requirements associated with the lunar mission.

In initial lunar operations the flying vehicle will be operated conservatively and cautiously (at short ranges, low speeds, and low altitudes). As lunar experience is gained longer range and higher speed sorties will be flown. Earth rocket belt and jet belt experience has demonstrated safe flight at altitudes up to 75 ft and speeds up to 100 ft/sec for VFR flight (flight without instruments). The question arises: "At what speeds, altitudes, and ranges, does it become necessary to add instrumentation and what kind of instrumentation is required for safe and efficient flight in the lunar environment?" It is therefore proposed that an early research program be implemented using a helicopter to acquire some preliminary information towards answering this question and to assist in defining a more comprehensive flight research program.

An early pilot training program using existing vehicles and facilities and NASA personnel (astronauts or

test pilots) as trainees would contribute towards a better definition of the flight research and training plan. This would serve the dual purpose of providing information for training plan refinement and introducing NASA personnel to manually controlled rocket powered flight. A ten week program involving the use of the visual simulation facility, the 1/6 g tether facility and vehicle, and the 1 g vehicle (with safety tether and free flights) is proposed to be conducted with two NASA trainees.

C. COMPARISON OF BELL AND NR VEHICLE HANDLING QUALITIES ON BELL SIMULATOR

NASA has provided a comparison of the lunar vehicle concepts recommended by Bell and North American, which indicates a difference in the flight control system approach. Bell has recommended a simple, mechanically linked, un-augmented, flight control system. North American has recommended a more complex, electrically linked, augmented, flight control system. Of considerable importance in selection of the best approach is an evaluation of the influence of the simulators used by Bell and North American in arriving at their respective recommendations. To aid in this evaluation, it is proposed to set up both the Bell and the North American vehicle and control system characteristics on the Bell visual simulator, and conduct flights using NASA subjects as pilots.

D. 1G FREE FLIGHT TESTS WITH A PRESSURE SUITED SUBJECT

The precision and safety with which a pilot in shirt-sleeves can control a small rocket supported flying vehicle, using a simple, all-mechanical thrust vector control system has been demonstrated by 10 pilots in over 3000 flights in earth gravity, in a variety of vehicle configurations, and by three pilots in over 60 flights in simulated lunar gravity with the Bell Pogo vehicle on the NASA-LLRF, and on a lunar tether and overhead trolley system at Bell. Pressure suited flight has been demonstrated by two pilots in 27 flights in simulated lunar gravity with the Bell Pogo vehicle on the NASA-LLRF. Free flight with a pressure suited pilot has not yet been attempted, because the thrust available in the Bell one man vehicle is insufficient to lift the added weight of a pressure suit and PLSS. Because of the low velocity, acceleration, and range limits of the lunar tether systems and other unwanted simulator side effects on the pilot, it is desirable that safety and precision be demonstrated by free flight with a pressure suited operator. Vehicle and control input motion data can be obtained during flight for the validation of ground based simulators.

It is proposed that the Bell two-man pogo be modified to carry one man in a pressure suit and PLSS.

E. EARLY FLYER HYDROGEN PEROXIDE PROPULSION SYSTEM

Recent flyer studies indicate that the Lunar Flyer will require rocket thrust of about 300 pounds. The present Bell Rocket Belt Hydrogen Peroxide Propulsion System provides 300 pounds thrust and has demonstrated extremely high reliability in over 3000 earth flight tests. Preliminary analysis indicates that the incorporation of the rocket belt hydrogen peroxide propulsion system on the One Man Lunar Flying Vehicle could provide an earlier operational Lunar Flyer, with minimum development risk. The vehicle would provide sufficient lunar performance capability to conduct useful scientific exploration, and to verify lunar flight handling qualities prior to incorporation of the later LM propellant system.

A design study is recommended to determine the application of each component to lunar environment, to install the system on the lunar vehicle, and to establish performance, cost, and schedule data.

F. FLYER ORIENTED APPLICATION ANALYSIS

Most previous lunar scientific mission studies have been conducted by personnel who were unfamiliar with flyers and assumed that exploration would be done on foot or with wheeled vehicles. Thus, scientific experiments were designed to be compatible with surface mobility. Bell funded studies have indicated that scientific time at remote sites can be extended, scientific return increased by in-flight remote sensing, and new experiments devised not possible with surface mobility, if experiments are designed with flying mobility as a consideration. In addition, several modes of surface rescue are available with a flyer, which could enhance total mission safety and probability of success. It is recommended that specific Apollo lunar landing sites be analyzed for application of flying mobility to increase remote site exploration time, to increase scientific return by accomplishing high resolution geologic reconnaissance by remote sensing during flight, and by accurate and rapid photographic in-flight survey of exploration sites, deployment of surface experiment packages, placing of seismic charges, etc. A study is recommended to establish methods of using a flyer for fast emergency return to LM of a walking or riding astronaut, for emergency aid of resupply to an EVA astronaut, and of the application of a stripped down minimum weight flying seat as the seat on a lunar roving vehicle, as an emergency return device.

G. LUNAR EXPLORATION SIMULATION USING FLYING MOBILITY

The U.S. Geological Survey Branch of Astrogeology at Flagstaff, Arizona, has conducted simulations of lunar

geological explorations using walking and surface vehicle mobility. No such simulation has been done using flying mobility. It is recommended that typical flying sorties be simulated, with a pressure suited subject, using a helicopter to provide the mobility which a lunar flyer would provide on the moon. This could be accomplished by having the subject ride as passenger in a helicopter, providing verbal commands to the helicopter pilot. He could thus simulate his ability to navigate and explore from the air, recognize items of interest, and evaluate the suitability of this type of exploration.

H. FULL SCALE MOCKUP/PRESSURE SUIT TESTS

A portion of the astronaut's EVA time will be consumed in unloading the lunar flying vehicle from the LM descent stage, and servicing the flyer with propellants and pressurizing gas. Time estimates to conduct these tests have been provided in the current flyer study by breaking the operation into specific subtasks required and estimating the time for each operation. However, estimates of time required for basic operations vary widely. A full scale simulation using a lunar weight vehicle and a pressure suited subject in a lunar gravity suspension is recommended to provide time line data with a higher degree of confidence, for use in mission planning.

I. HANDLING QUALITIES/CONTROL AUGMENTATION

The Bell study of the One Man Lunar Flying Vehicle has recommended a simple mechanically linked flight control system, demonstrated on thousands of free flights of rocket belts, Pogo vehicles, and flying chairs, and proven acceptable in simulated lunar gravity flight tests on the Langley Research Center LLRF. The system provides proportional command of vehicle angular acceleration, and does not include what is commonly called "stability augmentation." Stability augmentation results in command of vehicle angular rate commonly provided in space vehicles by using rate gyro feedback and electronic control systems. Bell tests in a visual simulation facility, to determine the benefit of stability augmentation for the lunar flyer, indicated that although handling qualities were acceptable without augmentation, the addition of augmentation decreased pilot workload and improved the pilot opinion rating of the vehicle.

Bell recommends further investigation of methods of incorporating stability augmentation in such a manner as to not degrade the inherent high reliability of the mechanical system.

It has been found, by analog simulation, that augmentation, can be provided by introducing a spring/damper

between the handle bar controller and the gimballed engines. This results in handling qualities equal to the electronic system. Additional investigation is required to determine the optimum parameters for flight control and trim control, and the mass and inertia effects of the engines on the spring damper system.

J. LANDING GEAR ANALYSIS

Bell has compared various vehicle and landing gear configurations using a digital computer program. This program analyzes landing dynamics in two dimensions, that is, in the pitch plane, and provides time histories of loads, deflections, and vehicle stability as a function of vehicle, landing gear, flight path, lunar surface, and soil parameters. It has been verified by comparison with previous analyses on other computer programs verified by model drop tests. In order to establish final landing gear design requirements, it is recommended to expand the Bell program to a three dimensional analysis to include vehicle yaw.

K. PROPULSION SYSTEM TESTING

Present One Man Lunar Flying Vehicle studies have established a requirement for rocket engines in the 150 lb thrust class, using LM propellants. Several vendors have demonstrated the capability of providing a throttleable engine of this size. However, in some cases the demonstrations of throttling were conducted by changing propellant feed pressure, a method not suitable to lunar vehicle use, and in other cases maximum engine operating temperature was higher than is desirable for maximum engine life. Since the engine/valve assembly is the single most costly component, and longest lead item on the lunar flyer, confidence in the program cost and schedule would be increased by early demonstration tests of an engine which meets the thrust, throttling, stability and temperature margin requirements of the lunar flyer.